

A semi-automatic implant design method for cranial defect restoration



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Purpose

The cranial defect restoration is required when a patient suffers from head trauma due to an accident or injury [1], [2]. However, the traditional method for the implant design is time consuming and complicated using industrial softwares such as Pro-Engineer (PTC, America), 3Matic (Materialise, Belgium), Geomagic Design (Geomagic, America), etc. [3], [4].

In this study, a semi-automatic implant design method for cranial defect restoration is presented, and a software named CranialCAD has been developed based on some well-known open-sourced toolkits including VTK (<http://www.vtk.org/>) and Qt (<http://qt-project.org/>). Aiming at evaluating the efficiency of our method, several case studies were conducted and the comparison with traditional ways was also discussed.

Methods

The workflow of our method is shown in Fig. 1, which is described as follows:

1. Mirroring model: The median plane is generated for the mirroring according to the anatomically symmetric points of the skull model. Given $N(x, y, z)$ is the normal of the plane, R is the vector of the rotation axis, and A is the rotation angle. The mirroring method is realized through a transform matrix T acquired from the equations below:

$$T = T_1 T_2 T_3 T^{-1} T_2^{-1} T_1^{-1} \quad (1)$$

$$R = \text{cross} \quad (2)$$

$$A = \text{atan}(\sqrt{(z^2 + y^2)/x}) / \pi * 180 \quad (3)$$

where T_1 , T_2 , T_3 are respectively the transform matrix for translating and rotating the model.

2. Clipping surface: A contour is indicated along the edge of the defect. An implicit function is constructed based on the signed distance field determined by the dot product of a vector V from Eq. (4) with the normal of vertex X . Using a vtk class named `vtkClipPolydata`, the mirrored model is clipped through the implicit function.

$$V = X - M \quad (4)$$

where M is the nearest point to X on the contour.

3. Surface fitting: Another contour is drawn around the defect region. The points inside the contour are projected on the screen to obtain the view coordinates and then converted into world coordinates to reduce the overlapped points. An initial model is reconstructed using Delaunay triangulation algorithm through the points.

4. Generation of the implant: The outer surface of initial implant is generated by clipping the initial model using the contour in step 3. An isosurface S defined from Eq. (5) is formed as the inner surface using MC algorithm.

$$S = \{(x, y, z) : f(x, y, z) = a\} \quad (5)$$

where $f(x, y, z)$ is the signed distance and a is the thickness of the implant. Ruled surface is used to connect the inner and outer surface of the initial implant. The final implant is obtained using the same method using another contour drawn from the inside of the initial implant along the edge of the defect.

Results

The CT data of a patient can be imported into CranialCAD to reconstruct the cranial model with defect based on image segmentation, region growing and marching cubes algorithm. First of all, a mirrored model is created according to the median plane, and then a surface is fitted on the basis of the region surrounding the skull defect, and the final implant is generated using surface clipping, surface offsetting, and ruled surface construction. On the basis of this method, the phantom experiments for four cases were conducted using the CranialCAD (shown in Fig.2 (a)-(d)), resulting in anatomically well-fitting and highly symmetric implants. The comparison study for the case (d) was also carried out between the implant designed using CranialCAD and the result (shown in Fig.2 (e)) using the traditional softwares of UG, Geomagic and Materialise Magic RP together. The distance color map (shown in Fig.2 (f)) shows that there is no significant difference at the edge of the implant model between two models. As our method is based on the mirrored model, the implant designed using CranialCAD is more symmetric than the traditional way.

In addition, only three manual steps of our method i.e., the median plane generation, and two contours' drawing, are required, making it much easier and more efficient. Generally, it takes less than 30 minutes to accomplish the whole design using CranialCAD, whereas at least 2~3 hours are needed when using traditional softwares.

Conclusion

In this study, a semi-automatic implant design method for cranial defect restoration was proposed. The phantom experiments validated the feasibility and efficiency of the CranialCAD. However, our method has limitation for a skull with large area defect near the temporal bone, as the surface fitting algorithm may fail since the surrounding surface is not convex. A similar workflow under Me VisLab showed great efficiency for the cranial implant planning, which can help us to improve the algorithm [5]. Nevertheless, future research still needs to be done and clinical trials aiming at evaluating the reliability of CranialCAD will be conducted. As the CranialCAD is developed on the basis of open sourced toolkits, it will be released as an extension module of 3D Slicer (an open sourced software platform for visualization and medical image computing, www.slicer.org) in the near future so that it can be shared by the global community.

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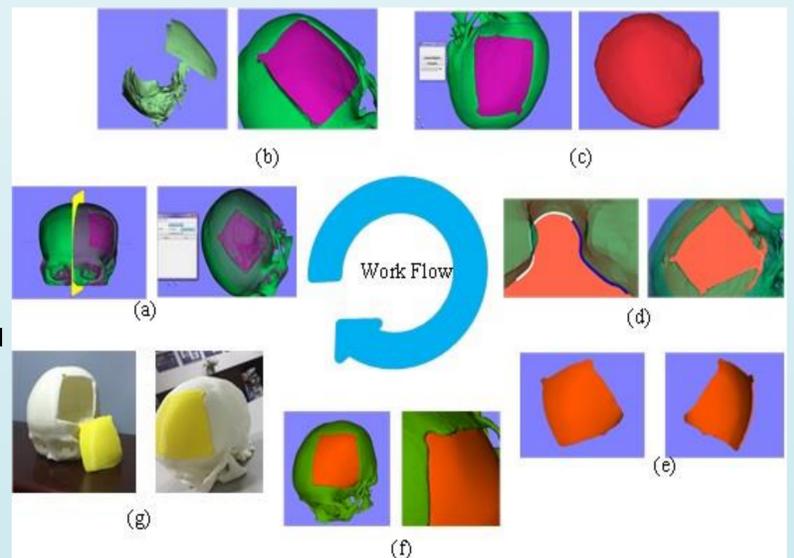


Fig. 1. – The work flow of CranialCAD: (a) mirroring the model; (b) clipping the mirrored model; (c) Surface fitting and the generation of the initial implant; (d) the generation of the final implant; (e) (f) the final cranial implant and restoration effect; (g) the 3D printed implant model

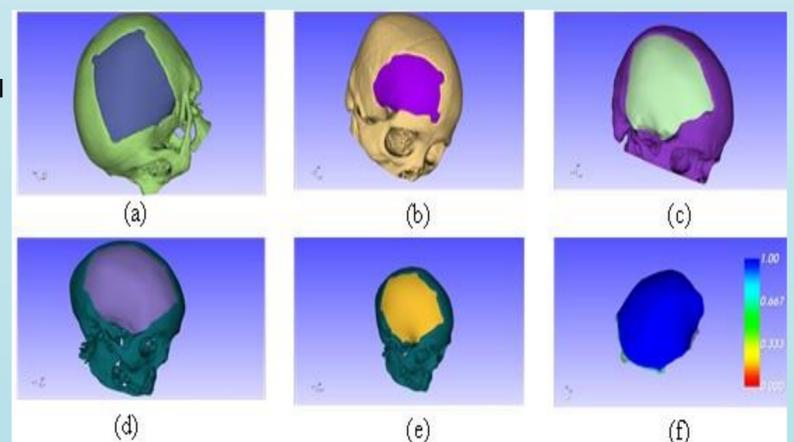


Fig. 2. – (a) (b) (c) (d): Phantom experiments for four cases using CranialCAD; (e) the implant design using traditional softwares; (f) the distance comparison between the two implants of (d) and (e)



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